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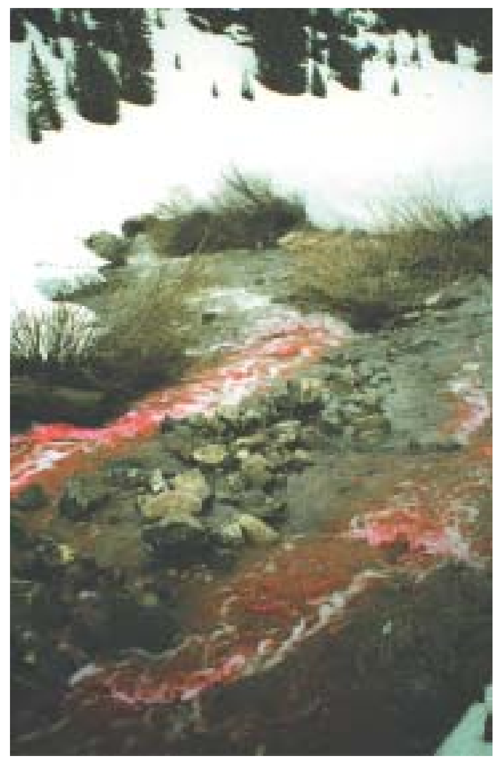
NATIONAL WATER-QUALITY ASSESSMENT PROGRAM

Traveltime Characteristics of Gore Creek and Black Gore Creek, Upper Colorado River Basin, Colorado



Water-Resources Investigations Report 02–4037

U.S. Department of the Interior
U.S. Geological Survey

Cover Photographs

Dye injection on Black Gore Creek. The dye will rapidly mix with stream water and become invisible as it moves downstream.
Photographs by Norman Spahr, U.S. Geological Survey.

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By Jason J. Gurdak, Norman E. Spahr, and Richard J. Szmajter

U.S. GEOLOGICAL SURVEY

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Denver, Colorado
2002

U.S. DEPARTMENT OF THE INTERIOR
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FOREWORD

The mission of the U.S. Geological Survey (USGS) is to assess the quantity and quality of the earth resources of the Nation and to provide information that will assist resource managers and policymakers at Federal, State, and local levels in making sound decisions. Assessment of water-quality conditions and trends is an important part of this overall mission.

One of the greatest challenges faced by water-resources scientists is acquiring reliable information that will guide the use and protection of the Nation's water resources. That challenge is being addressed by Federal, State, interstate, and local water-resource agencies and by many academic institutions. These organizations are collecting water-quality data for a host of purposes that include: compliance with permits and water-supply standards; development of remediation plans for specific contamination problems; operational decisions on industrial, wastewater, or water-supply facilities; and research on factors that affect water quality. An additional need for water-quality information is to provide a basis on which regional- and national-level policy decisions can be based. Wise decisions must be based on sound information. As a society we need to know whether certain types of water-quality problems are isolated or ubiquitous, whether there are significant differences in conditions among regions, whether the conditions are changing over time, and why these conditions change from place to place and over time. The information can be used to help determine the efficacy of existing water-quality policies and to help analysts determine the need for and likely consequences of new policies.

To address these needs, the U.S. Congress appropriated funds in 1986 for the USGS to begin a pilot program in seven project areas to develop and refine the National Water-Quality Assessment (NAWQA) Program. In 1991, the USGS began full implementation of the program. The NAWQA Program builds upon an existing base of water-quality studies of the USGS, as well as those of other Federal, State, and local agencies. The objectives of the NAWQA Program are to:

- Describe current water-quality conditions for a large part of the Nation's freshwater streams, rivers, and aquifers.
- Describe how water quality is changing over time.
- Improve understanding of the primary natural and human factors that affect water-quality conditions.

This information will help support the development and evaluation of management, regulatory, and monitoring decisions by other Federal, State, and local agencies to protect, use, and enhance water resources.

The goals of the NAWQA Program are being achieved through ongoing and proposed investigations of 59 of the Nation's most important river basins and aquifer systems, which are referred to as study units. These study units are distributed throughout the Nation and cover a diversity of hydrogeologic settings. More than two-thirds of the Nation's freshwater use occurs within the 59 study units and more than two-thirds of the people served by public water-supply systems live within their boundaries.

National synthesis of data analysis, based on aggregation of comparable information obtained from the study units, is a major component of the program. This effort focuses on selected water-quality topics using nationally consistent information. Comparative studies will explain differences and similarities in observed water-quality conditions among study areas and will identify changes and trends and their causes. The first topics addressed by the national synthesis are pesticides, nutrients, volatile organic compounds, and aquatic biology. Discussions on these and other water-quality topics will be published in periodic summaries of the quality of the Nation's ground and surface water as the information becomes available.

This report is an element of the comprehensive body of information developed as part of the NAWQA Program. The program depends heavily on the advice, cooperation, and information from many Federal, State, interstate, Tribal, and local agencies and the public. The assistance and suggestions of all are greatly appreciated.

Robert M. Hirsch
Chief Hydrologist

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FIGURES

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CONVERSION FACTORS AND ABBREVIATIONS

Multiply	By	To obtain
foot (ft)	0.3048	meter
foot per second (ft/s)	0.3048	meter per second
square foot per second (ft^2/s)	0.0929	square meter per second
mile per hour (mph)	1.609	kilometer per hour
cubic foot (ft^3)	0.02832	cubic meter
gallon (gal)	3.785	liter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per second (ft^3/s)	28.32	liter per second
square mile (mi^2)	2.59	square kilometer
pound (lb)	0.454	kilogram

ADDITIONAL ABBREVIATIONS OR TERMS

mg/L, milligrams per liter
mL, milliliters
Q, discharge
s, seconds
μg/L, micrograms per liter
>, greater than

Traveltime Characteristics of Gore Creek and Black Gore Creek, Upper Colorado River Basin, Colorado

By Jason J. Gurdak, Norman E. Spahr, *and* Richard J. Szmajter

Abstract

In the Rocky Mountains of Colorado, major highways are often constructed in stream valleys. In the event of a vehicular accident involving hazardous materials, the close proximity of highways to the streams increases the risk of contamination entering the streams. Recent population growth has contributed to increased traffic volume along Colorado highways and has resulted in increased movement of hazardous materials, particularly along Interstate 70.

Gore Creek and its major tributary, Black Gore Creek, are vulnerable to such contamination from vehicular accidents along Interstate 70. Gore Creek, major tributary of the Eagle River, drains approximately 102 square miles, some of which has recently undergone significant urban development. The headwaters of Gore Creek originate in the Gore Range in the eastern part of the Gore Creek watershed. Gore Creek flows west to the Eagle River. Beginning at the watershed boundary on Vail Pass, southeast of Vail Ski Resort, Interstate 70 parallels Black Gore Creek and then closely follows Gore Creek the entire length of the watershed. Interstate 70 crosses Gore Creek and tributaries 20 times in the watershed.

In the event of a vehicular accident involving a contaminant spill into Gore Creek or Black Gore Creek, a stepwise procedure has been developed for water-resource managers to estimate traveltimes of the leading edge and peak concentration of a conservative contaminant. An example calculating estimated traveltimes for a hypothetical contaminant release in Black Gore Creek is provided.

Traveltime measurements were made during May and September along Black Gore Creek and Gore Creek from just downstream from the Black Lakes to the confluence with the Eagle River to account for seasonal variability in stream discharge. Fluorometric dye injection of rhodamine WT and downstream dye detection by fluorometry were used to measure traveltime characteristics of Gore Creek and Black Gore Creek. During the May traveltime measurements, discharges ranged from 82 cubic feet per second (ft^3/s) at Black Gore Creek near Minturn (U.S. Geological Survey station number 09066000) to 724 ft^3/s at Gore Creek at mouth near Minturn (U.S. Geological Survey station number 09066510), whereas during the September traveltime measurements, discharges ranged from 3.6 ft^3/s at Black Gore Creek near Minturn to 62 ft^3/s at Gore Creek at mouth near Minturn. Cumulative traveltimes for the peak dye concentration during the May traveltime measurements ranged from 3.45 hours (site 1 to site 3) in Black Gore Creek to 2.50 hours (site 8 to site 12) in Gore Creek, whereas cumulative traveltimes for the peak dye concentration during the September traveltime measurements ranged from 15.33 hours (site 1 to site 3) in Black Gore Creek to 8.65 hours (site 8 to site 12) in Gore Creek. During the September dye injections, beaver dams on Black Gore Creek, between site 1 and the confluence with Gore Creek, substantially delayed movement of the rhodamine WT.

Estimated traveltimes were developed using relations established from linear-regression methods of relating measured peak traveltime to discharge during those measurements, which were obtained at Black Gore Creek near Minturn and Gore Creek at mouth near Minturn. Resulting estimated peak traveltimes for Black Gore Creek (sites 1 to 5) ranged from 5.4 to 0.4 hour for 20 to 200 ft^3/s and for Gore Creek (sites 5 to 12), 5.5 to 0.3 hour for 20 to 800 ft^3/s.

Longitudinal-dispersion coefficients that were calculated for selected stream reaches ranged from 17.2 square feet per second at 4 ft^3/s between sites 2 and 3 to 650 square feet per second at 144 ft^3/s between sites 7 and 8. Longitudinal-dispersion coefficients are necessary variables for future stream-contaminant modeling in the Gore Creek watershed.

INTRODUCTION

In the Rocky Mountains of Colorado, major highways are often constructed in stream valleys. In the event of a vehicular accident involving hazardous materials, the close proximity of highways to the streams increases the risk of contamination entering the streams. Such a spill could have a deleterious effect on downstream water-quality conditions.

Recent population growth has contributed to increased traffic volume along Colorado highways and has resulted in increased movement of hazardous materials, particularly along Interstate 70. Vehicular accidents involving hazardous materials are more likely to occur in variable driving conditions, which are particularly common in mountainous regions. Low grade highways constructed in stream valleys typically become more steep closer to the headwaters and typically traverse a mountain pass. Mountain passes present significant driving challenges, as these steeply graded and winding roads often are subject to poor driving conditions due to wind, snow, and ice.

Population growth also puts extra demands on the quality and quantity of water resources. Mountain communities commonly rely on surface water for drinking-water supplies. The same streams used for drinking water support recreational activities and the tourism-based economies of many mountain communities. Local tourism depends heavily on water-related recreation, such as fishing and skiing (stream water is used in snow-making), which are dependent on water quality.

Water-resource managers must be prepared to manage a near-stream hazardous spill because streamflow can quickly carry contaminants to downstream communities, where public water supplies could be affected. The ability to estimate accurately the downstream rate of travel of a hazardous material plume is essential to minimize the effects of spills on downstream water supplies. Protective actions, such as closing water-intake valves, may be required before a spill reaches a vulnerable downstream point.

Gore Creek and its major tributary, Black Gore Creek, are vulnerable to such contamination because Interstate 70 closely parallels these two streams from the headwaters on Vail Pass, through the Vail Ski Resort, to the confluence with the Eagle River (fig. 1). Interstate 70 crosses Gore Creek and tributaries 20 times in the Gore Creek watershed and can be a source of contaminants, such as sand, deicing salts, motor-oil, and chemical spills. Thus, because traveltime information was not available for Gore Creek and Black Gore Creek to assist water-resource managers in the event of a hazardous spill, the U.S. Geological Survey (USGS) conducted a traveltime study as a part of the Upper Colorado River Basin National Water-Quality Assessment study.

Purpose and Scope

The purpose of this report is to present traveltime and longitudinal-dispersion characteristics for 11 stream reaches in Black Gore Creek and Gore Creek. The results of the traveltime measurements were used to estimate the traveltime of potential contaminant releases in Black Gore Creek and Gore Creek and to calculate longitudinal dispersion coefficients. During May and September 1997, traveltime measurements were conducted along Black Gore Creek and Gore Creek from a site just downstream from the Black Lakes to the confluence with the Eagle River (fig. 1) to account for seasonal variability in stream discharge. These measurements were conducted at 12 sites, over approximately 18.2 miles of stream (11.4 miles on Gore Creek and 6.8 miles on Black Gore Creek). Table 1 lists traveltime sites and their locations on Black Gore Creek and Gore Creek.

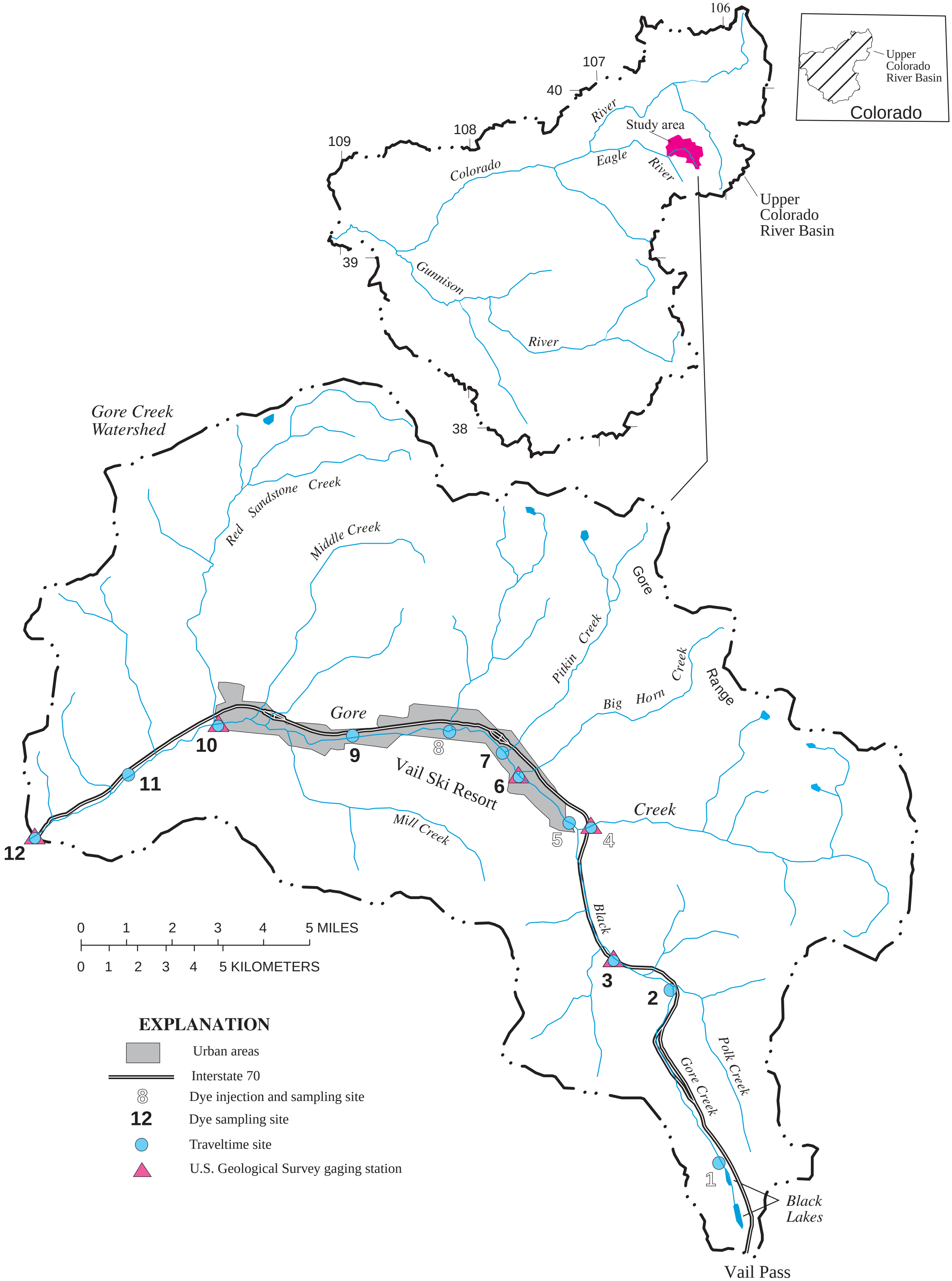

Figure 1. Location of study area and dye injection and sampling sites in the Gore Creek watershed.

Table 1. Traveltime sites on Black Gore Creek and Gore Creek, Colorado

[na, not applicable]

Site no. (fig. 1)	Site name	U.S. Geological Survey station number	Distance upstream from mouth of Gore Creek (river miles)	Latitude	Longitude
1	Black Gore Creek below Black Lake	393307106133200	18.24	39° 33'07"	106° 13'32"
2	Black Gore Creek at Polk Creek	393527106143500	14.81	39° 35'27"	106° 14'35"
3	Black Gore Creek near Minturn	09066000	13.78	39° 25'47"	106° 15'52"
4	Gore Creek at upper station, near Minturn	09065500	11.65	39° 37'33"	106° 16'39"
5	Gore Creek below Black Gore Creek	393737106165900	11.20	39° 37'37"	106° 16'59"
6	Bighorn Creek near Minturn	09066100	10.07	39° 38'24"	106° 17'34"
7	Gore Creek at Bighorn subdivision	393831106181900	9.47	39° 38'31"	106° 18'19"
8	Gore Creek at well field	393844106192100	8.36	39° 38'44"	106° 19'21"
9	Gore Creek at golf course entrance	na	6.69	39° 38'32"	106° 21'07"
10	Gore Creek at lower station, at Vail	09066310	4.13	39° 38'28"	106° 23'37"
11	Gore Creek at West Vail exit	393738106251000	2.13	39° 37'38"	106° 25'10"
12	Gore Creek at mouth near Minturn	09066510	0.09	39° 36'37"	106°26'46"

Study Area

The Gore Creek watershed encompasses approximately 102 mi^2 in the Upper Colorado River Basin, some of which has recently undergone significant urban development. The headwaters of Gore Creek originate in the Gore Range in the eastern part of the Gore Creek watershed. Gore Creek flows west to the confluence with the Eagle River. Land-surface elevation in the Gore Creek watershed ranges from 13,300 ft in the Gore Range to 7,720 ft at the confluence with the Eagle River. Hydrology of the watershed is highly variable because of steep-gradient topography and large seasonal variation in stream discharge. Seasonal variation in stream discharge results from accumulation of deep snowpack during winter and large runoff during spring and summer from melting of the snowpack. Stream morphology also is variable, with significant downstream changes in bed material, channel shape, and ponded features such as natural and manmade pools and dams.

Water quality, biological health, and overall esthetic value of Gore Creek are of major concern to local residents. Gore Creek has been identified as having a healthy and diverse biological community. Due to an exceptional brown trout community, the Colorado Division of Wildlife has designated the lower 4-mile reach of Gore Creek a Gold Medal trout fishery. During the past few decades, sections of the Gore Creek watershed have been developed for recreation and tourism uses. The population in Eagle County has increased by 59 percent between 1990 (21,928) and 1999 (34,950) (U.S. Bureau of the Census, 2000). Much of this growth has occurred near Gore Creek and its tributaries.

Acknowledgments

The authors thank Bob Boulger, Nancy Driver, Jeff Foster, and Barbara Ruddy, USGS, for collection of dye samples. Acknowledgments also are extended to Mary A. Kidd for editorial review, Alene J. Brogan for manuscript and layout, and Sharon M. Clendening for graphic design.

THEORY AND METHODS FOR DETERMINATION OF TRAVELTIME AND LONGITUDINAL-DISPERSION CHARACTERISTICS

Traveltime and longitudinal-dispersion characteristics of a stream vary with flow conditions. Therefore, traveltime and longitudinal-dispersion characteristics for a stream reach are determined by measuring the rate of movement and dispersion of a substance injected into a stream for a range of flow conditions.

Tracer Theory

A conservative dye tracer, such as rhodamine WT, acts as a solute, completely mixing with the stream and simulating movement and dispersion of water particles. Monitoring the shape and speed of a resulting dye-tracer cloud determines movement and dispersion of dissolved elements within the stream. Therefore, characteristics of dye-tracer clouds, such as traveltime and longitudinal-dispersion coefficients, reveal the movement and dispersion of potential conservative contaminants that may enter a stream (Ruddy and Britton, 1989).

Traveltime

Traveltime measurements are necessary to characterize movement of dissolved contaminants (solutes) that may enter a stream. For this study, traveltime is defined as elapsed time (in hours) for the travel of a solute from the point of injection to the next downstream sampling point. Cumulative traveltime is defined as traveltime from injection to any given downstream sampling point of interest. Traveltime measures elapsed time of travel for a given solute, whereas velocity of a solute measures the rate (distance per time) of travel. Stream velocity measures the rate of downstream travel of water particles in a given stream reach. Stream velocity is highly variable and is dependent on storage, channel shape, slope, morphology, and streambed materials. Ponded features, such as manmade or beaver dams, can significantly alter stream velocity. Solute traveltimes can be estimated by using stream velocity determined from discharge measurements, but this method often provides inaccurate results. To more accurately determine traveltime and account for inherent variability in stream velocity, dye-tracer techniques are used.

The shape and speed of a typical dye-tracer cloud resulting from an instantaneous injection is shown in figure 2, which shows the leading edge, peak concentration, and trailing edge. The traveltime for the leading edge of a dye tracer is when the cloud first reaches a specific point on a stream and, according to Jobson (1996), is approximately 89 percent of the peak concentration traveltime. Traveltime of the peak

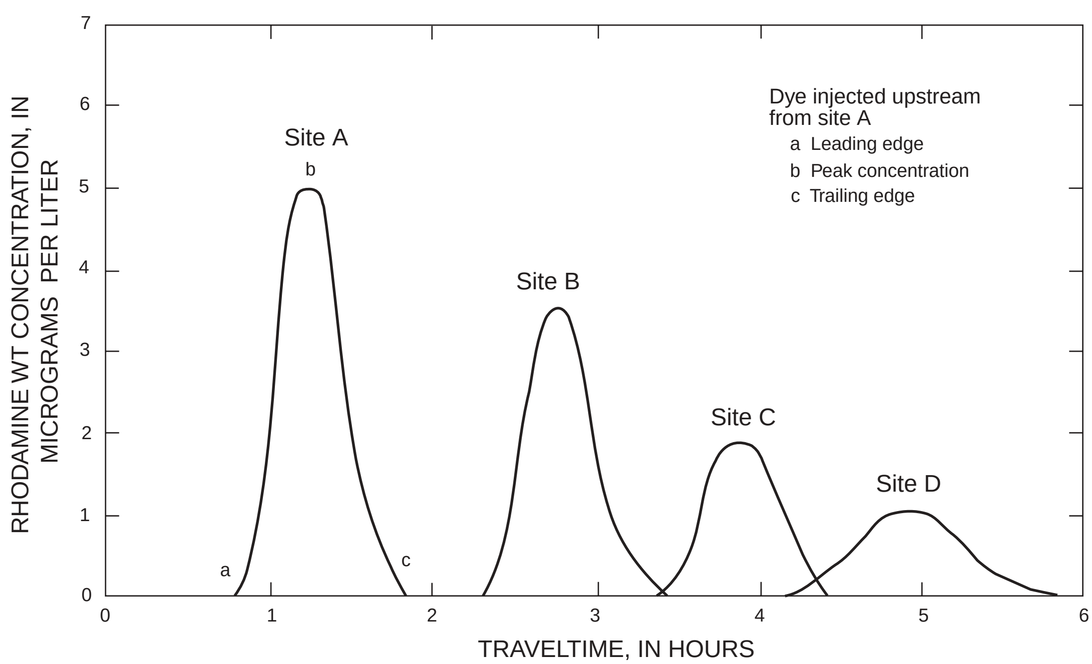

Figure 2. Typical dye response curves (sites A to D) resulting from an instantaneous upstream injection of tracer.

concentration is when the highest concentration of the dye reaches a specific point on a stream. The difference between the traveltime of the trailing edge and the leading edge of the curve represents the time of passage at a specific point on a stream. Characteristics of a conservative dye curve can be applied to estimate the traveltime characteristics of other conservative solutes in that stream.

Longitudinal Dispersion

Longitudinal dispersion is the process whereby a mass of solute introduced into a flowing stream is mixed and diluted in the longitudinal, or downstream, direction (Nordin and Sabol, 1974). Immediately following a slug injection, a dye tracer simultaneously disperses in all three dimensions. Complete mixing in the vertical direction normally occurs first. Although dispersion of a solute typically depends on specific stream characteristics and velocity variations, complete lateral mixing typically occurs second. Dispersion in the longitudinal direction continues infinitely, as it has no boundaries. A typical dye curve as shown in figure 2, illustrates longitudinal-dispersion effects. As the dye travels downstream, a decrease in peak concentration occurs as the cloud spreads and disperses longitudinally along the stream reach.

The longitudinal dispersion of a particular stream reach can be described by a longitudinal-dispersion coefficient, K_x, with which the degree of dispersion can be estimated. Longitudinal-dispersion coefficients are independent of concentration and time, representing the rate of dilution of a soluble substance into a stream by means of mixing in an increasing volume of water as the dye cloud lengthens (Nordin and Sabol, 1974). Longitudinal-dispersion coefficients are estimated by the following equation:

$$K_x = (\overline{U}^{\,2} / 2) d(\sigma_t^2) / (dt) \qquad (1)$$

where

K_x = longitudinal-dispersion coefficient, in square feet per second;

$\overline{U}$ = mean peak velocity of dye cloud, in feet per second;

σ_t^2 = variance of dye cloud concentration with respect to time, in seconds squared; and

dt = change in time, in seconds.

Equation 1 is assumed to approximate the longitudinal-dispersion coefficient only after adequate mixing time is allowed. Immediately following injection, dispersion of the dye occurs at a faster rate than the stream velocity. Therefore, calculations for longitudinal-dispersion coefficients are only valid on stream reaches that have had adequate mixing time during which the dye tracer has uniformly mixed in the lateral direction (Fischer, 1973).

Methods Used in the Gore Creek Watershed

This traveltime study used a fluorometric dye injection and downstream dye detection by fluorometry to measure traveltime characteristics of Gore Creek and Black Gore Creek. Fluorometry is a widely accepted technique for stream traveltime measurements, as it provides simple and accurate stream-tracer detection at low concentrations of dye (Wilson and others, 1986). A slug of a fluorometric dye, rhodamine WT, was instantaneously injected at sites 1, 5, and 8 during May 1997 and at sites 1, 4, and 8 during September 1997. Rhodamine WT is a conservative solute that is widely used in dye-tracing studies owing to a high detectability, good diffusivity, low sorptivity, and environmental safety (Wilson and others, 1986). However, the fluorescence of rhodamine WT is temperature dependent, resulting in slightly higher fluorescence readings at low water temperatures.

At sites downstream from dye-injection points, grab samples were collected from the approximate center of flow and fluorometry measurements were conducted using a Turner Designs Model 10 Fluorometer. Onsite fluorometry measurements aided in collecting samples at times that would distribute grab samples along the dye-curve profile. The onsite measurements were used to determine traveltimes of the leading edge and peak concentration of the dye cloud. To avoid temperature-dependent variations in fluorescence, a portion of each grab sample was analyzed at room temperature in the laboratory. More thorough descriptions of fluorometry, rhodamine WT, dye-tracer theory, and sampling techniques used during this study are presented by Wilson and others (1986) and Kilpatrick and Wilson (1989).

Average stream velocities between two sites were calculated by dividing the distance in river miles between sites by the traveltime of the peak dye concentration between the two sites. Discharges for Gore Creek and Black Gore Creek were available from four USGS streamflow-gaging stations. These gages (table 1) are site 3, Black Gore Creek near Minturn (09066000); site 4, Gore Creek at upper station, near Minturn (09065500); site 10, Gore Creek at lower station, at Vail (09066310) (discontinued); and site 12, Gore Creek at mouth near Minturn (09066510). Index discharge values, required to develop linear-regression relationships for estimation of traveltimes, are defined as the representative discharge conditions for the period of time during the actual dye injections in Gore Creek and Black Gore Creek. The two gages used to develop index discharge values were sites 3 and 12. The variance of the dye cloud was calculated and used in estimating longitudinal-dispersion coefficients (eq. 1).

TRAVELTIME

Spatial and temporal variations in stream discharge are apparent by comparison of daily mean discharge at three gages along Gore Creek and Black Gore Creek (fig. 3). Downstream reaches in the watershed have higher discharge during the same time period than upstream reaches. Tributaries other than Black Gore Creek (fig. 1) contribute substantial streamflow to Gore Creek. Relatively higher discharge occurs throughout the basin during May and June and represents springtime snowmelt.

Traveltime Measurements

Average velocity of the peak dye concentration during the May traveltime measurements ranged from 1.20 mph at site 2 on Black Gore Creek to 3.5 mph at site 12 on Gore Creek (table 2), whereas during the September traveltime measurements, average velocity of the peak dye concentration ranged from 0.29 mph at sites 2 and 3 on Black Gore Creek to 1.02 mph at site 12 on Gore Creek (table 3). Although dependent upon discharge and the distance between sites, high average velocities of peak dye concentration typically translated into short traveltimes. During the May traveltime measurements, discharges ranged from 82 ft^3/s at Black Gore Creek near Minturn to 724 ft^3/s at Gore Creek at mouth near Minturn (table 2), whereas during the September traveltime measurements, discharges ranged from 3.6 ft^3/s at Black Gore Creek near Minturn to 62 ft^3/s at Gore Creek at mouth near Minturn (table 3). Cumulative traveltimes for the peak

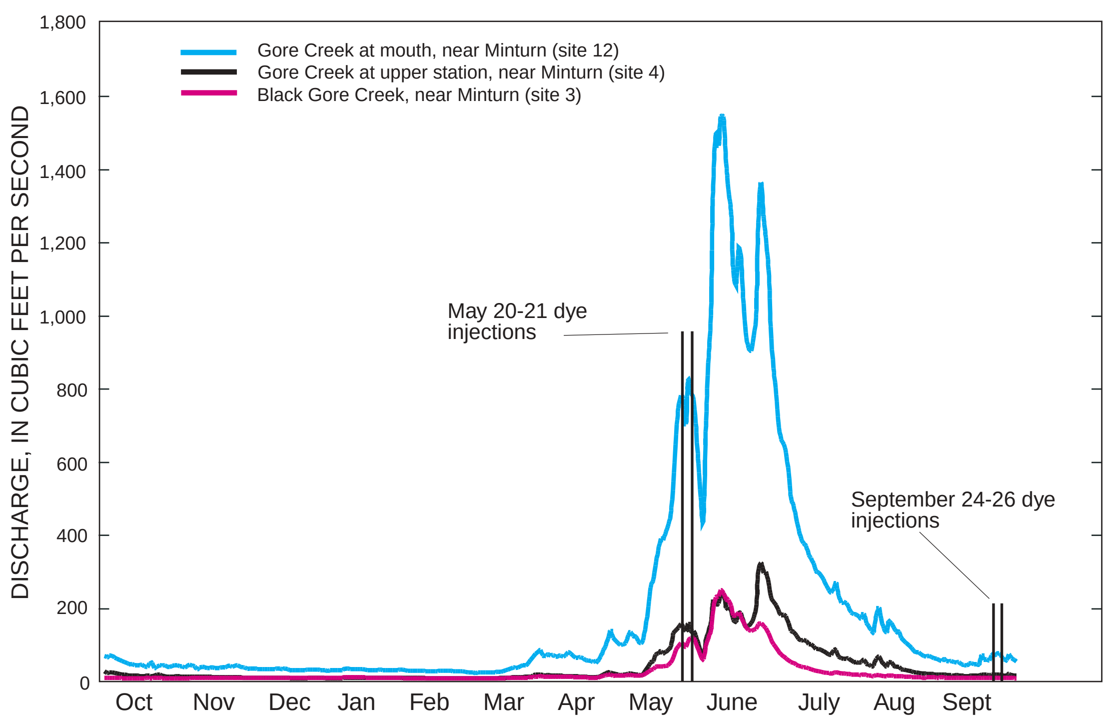

Figure 3. Daily mean discharge for Black Gore Creek and Gore Creek during water year 1997.

Table 2. Traveltime data for the May 20 and 21, 1997, dye injections

[--, no data; mph, miles per hour; mL, milliliters; Q, discharge; ft^3/s, cubic feet per second]

Site no. (table 1 and fig. 1)	Distance from injection point (river miles)	Cumulative traveltime of dye cloud (hours)				Average velocity of peak between adjacent sites (mph)	Variance of dye cloud between adjacent sites (hour, squared)
		Leading edge	Peak	Trailing edge	Centroid		
Injection of 100 mL of 20-percent solution rhodamine WT at site 1 at 10:02 a.m. May 21, 1997 (Black Gore Creek near Minturn, site 3, Q = 82 ft^3/s)							
1	--	--	--	--	--	--	--
2	3.43	2.45	2.85	3.75	2.96	1.20	0.04
3	4.46	3.03	3.45	4.50	3.52	1.72	0.05
5	7.04	4.18	4.63	6.07	4.79	2.19	0.09
6	8.17	4.53	5.00	6.38	5.15	3.05	0.09
Injection of 100 mL of 20-percent solution rhodamine WT at site 5 at 14:50 p.m. May 20, 1997 (Gore Creek at lower station at Vail, site 10, Q = 532 ft^3/s)							
5	--	--	--	--	--	--	-
6	1.13	0.25	0.33	0.57	0.37	3.42	0.002
7	1.73	0.47	0.60	0.88	0.61	2.22	0.004
8	2.84	0.77	1.02	1.60	1.04	2.64	0.01
9	4.51	1.30	1.52	2.17	1.58	3.34	0.02
Injection of 300 mL of 20-percent solution rhodamine WT at site 8 at 10:50 a.m. May 20, 1997 (Gore Creek at mouth near Minturn, site 12, Q = 724 ft^3/s)							
8	--	--	--	--	--	--	--
9	1.67	0.38	0.48	0.77	0.51	3.48	0.004
10	4.23	1.12	1.28	1.85	1.36	3.20	0.01
11	6.23	1.68	1.92	2.52	1.96	3.13	0.02
12	8.27	2.20	2.50	3.20	2.55	3.50	0.03

dye concentration during the May traveltime measurements ranged from 3.45 hours (site 1 to site 3) in Black Gore Creek to 2.50 hours (site 8 to site 12) in Gore Creek (table 2), whereas cumulative traveltimes for the peak dye concentration during the September traveltime measurements ranged from 15.33 hours (site 1 to site 3) in Black Gore Creek to 8.65 hours (site 8 to site 12) in Gore Creek (table 3). Cumulative traveltime of the centroid, which is the center of mass of the dye injection, closely approximated the cumulative traveltime of the peak dye concentration (tables 2 and 3).

Beaver dams, which may seasonally change in size and location, act as major storage basins for solutes and potential contaminants. During the September dye injections, beaver dams on Black Gore Creek between site 1 and the confluence with Gore Creek substantially delayed movement of the rhodamine WT. For example, traveltime of the peak dye concentration from site 1 to site 3 (4.46 river miles) was 3.45 hours in May and 15.33 hours in September (fig. 4), due in part to the delays caused by the beaver dams and lower discharge in September than in May. Because of these obstructions on Black Gore Creek, the second rhodamine WT injection during September was injected at site 4, Gore Creek gage at upper station, near Minturn. Due to the change in dye-injection location, traveltime measurements were not made during the September low-flow conditions from site 3 on Black Gore Creek to the confluence with Gore Creek. However, an estimate of traveltime was calculated for the stream reach from site 3 to site 5 of Black Gore Creek, and the estimate is discussed in the "Estimated Traveltimes" section.

Estimated Traveltimes

The primary goal of a traveltime study is to provide methods to estimate traveltime for a broad range of discharges. Traveltime data presented in tables 2 and 3 have a limited use because only

Table 3. Traveltime data for the September 24–26, 1997, dye injections

[--, no data; mph, miles per hour; mL, milliliters; Q, discharge; ft^3/s, cubic feet per second]

Site no. (table 1 and fig. 1)	Distance from injection point (river miles)	Cumulative traveltime of dye cloud (hours)				Average velocity of peak between adjacent sites (mph)	Variance of dye cloud between adjacent sites (hour, squared)
		Leading edge	Peak	Trailing edge	Centroid		
Injection of 80 mL of 20-percent solution rhodamine WT at site 1 at 05:25 a.m. September 25, 1997 (Black Gore near Minturn, site 3, Q = 3.6 ft^3/s)							
1	--	--	--	--	--	--	--
2	3.43	10.08	11.83	20.50	12.91	0.29	3.07
3	4.46	13.50	15.33	22.50	16.20	0.29	3.19
Injection of 80 mL of 20-percent solution rhodamine WT at site 4 at 07:25 a.m. September 26, 1997 (Gore Creek at lower station at Vail, site 10, Q = 44 ft^3/s)							
4	--	--	--	--	--	--	--
5	0.45	0.32	0.50	0.83	0.52	0.90	0.01
6	1.58	1.50	1.90	2.95	1.99	0.81	0.05
7	2.18	2.35	2.85	4.10	2.96	0.63	0.07
8	3.29	3.80	4.42	6.85	4.70	0.71	0.33
9	4.96	5.65	6.55	9.64	6.86	0.78	0.49
Injection of 100 mL of 20-percent solution rhodamine WT at site 8 at 07:50 a.m. September 24, 1997 (Gore Creek at mouth near Minturn, site 12, Q = 62 ft^3/s)							
8	--	--	--	--	--	--	--
9	1.67	1.25	1.79	3.05	1.93	0.93	0.07
10	4.23	3.83	4.67	6.70	4.84	0.88	0.20
11	6.23	5.67	6.65	9.25	6.85	1.01	0.28
12	8.27	7.67	8.65	11.25	8.84	1.02	0.31

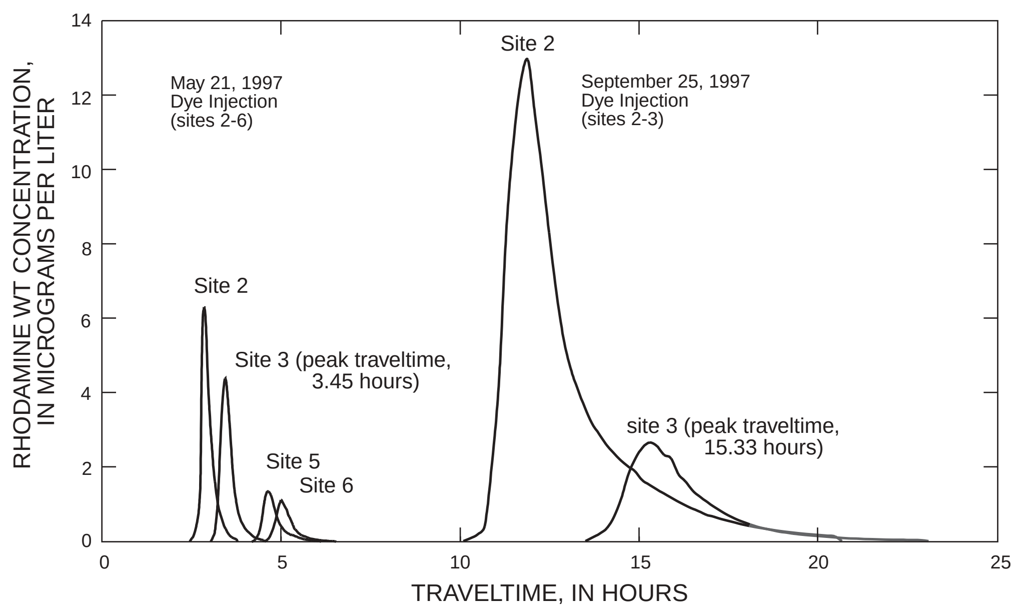

Figure 4. Dye response curves, May 21 and September 25, 1997.

discharge conditions measured during the traveltime measurements are represented. Water-resource managers could benefit from estimated traveltimes for a range of discharges in Gore Creek and Black Gore Creek.

Estimated traveltimes for peak concentration of rhodamine WT dye were calculated for discharges ranging from 20 to 800 ft^3/s for selected stream reaches. Estimated traveltimes were developed using relations established from linear-regression methods by relating measured peak traveltime to discharge from sites 3 and 12. Resulting estimated peak traveltimes for Black Gore Creek (sites 1 to 5) ranged from 5.4 to 0.4 hour for discharges of 20 to 200 ft^3/s (table 4) and for Gore Creek (sites 5 to 12), 5.5 to 0.3 hour for discharges of 20 to 800 ft^3/s (table 5). The discharge ranges of 20 to 200 ft^3/s and 20 to 800 ft^3/s are representative of the index discharge of Black Gore Creek and Gore Creek during respective dye injection and traveltime measurements. Although most hydrologic conditions for Black Gore Creek and Gore Creek are included within these ranges, discharge during peak spring runoff can be greater (fig. 3). Estimated traveltimes are not provided in tables 4 and 5 for discharge conditions representative of spring runoff (discharge greater than 800 ft^3/s) because of limitations in extrapolating beyond the range of measured values.

Traveltime measurements were not conducted between site 3 and site 5 on Black Gore Creek during September because of the presence of beaver dams. In developing estimated traveltimes for this reach (site 3 to site 5), the average velocity of the peak concentration between the two sites was assumed to equal that between site 5 and site 6 during the September traveltime measurements. This assumed average velocity of the peak concentration was divided by the actual distance (river miles) between site 3 and site 5 to estimate a measured traveltime, which was then used in the linear-regression method to develop estimated traveltimes between sites 3 and 5 (table 4). The assumption that the average velocity of the peak concentration between sites 3 and 5 was equal to that between sites 5 and 6 results in conservative traveltime estimates for use when predicting the rate of downstream travel of a potential contaminant plume originating in upstream reaches of Black Gore Creek.

The estimated traveltimes of the peak dye concentrations (tables 4 and 5) will provide water-resource managers with the necessary information to best approximate the rate of travel of hazardous spills. In the event of a spill, a stepwise procedure has been developed for water-resource managers to calculate estimated traveltimes of the leading edge and peak concentration of that spill. In developing this procedure, the contaminant was assumed to be conservative and the rate of spill was instantaneous. During the downstream transport of an actual spill, losses of the contaminant could occur by adsorption onto the streambed, volatilization, photochemical decay, and other chemical and physical processes.

Traveltime Estimation Example

Assume a tanker truck crashes and spills its cargo into Black Gore Creek, approximately 3 miles downstream from Black Lakes on Vail Pass (fig. 1). A surface-water diversion for irrigation is located near site 8 on Gore Creek. Operators of the water diversion want to know when to expect the leading edge and peak concentration of the contaminant plume at the diversion point so diverting contaminated water can be avoided.

This example involves estimating the traveltime along Black Gore Creek from the spill to the mouth of Black Gore Creek and the traveltime along Gore Creek from the confluence of Black Gore Creek to the site of interest. The following steps can be used to determine the traveltime of the peak and leading edge of the contaminant.

Step 1. Using figure 1 and table 1, determine: (A) the location of the spill, (B) the closest study site upstream from the spill, and (C) the closest study site to the downstream point of interest.

A. Approximate location of spill: **3 miles downstream from Black Lake** (from fig. 1)

B. Closest upstream study site from the spill: **site 1, Black Gore Creek below Black Lake** (from fig. 1)

C. Closest study site to downstream point of interest: **site 8, Gore Creek at well field** (from fig. 1)

Step 2. Determine traveltime for Black Gore Creek.

A. Determine discharge of Black Gore Creek at time of spill.

Use site 3, Black Gore Creek near Minturn.

Real-time streamflow data can be obtained on the internet at the USGS Colorado

Table 4. Estimated traveltimes of peak dye concentration in Black Gore Creek and Gore Creek, Colorado

[Discharge from Black Gore Creek near Minturn 09066000 (site 3); traveltime and cumulative traveltime in hours; shaded areas refer to "Traveltime Estimation Example"; --, no data; ft^3/s, cubic feet per second]

Site no. (table 1 and fig. 1)	Discharge, ft^3/s											
	20		40		60		80		100		200	
	Traveltime	Cumulative traveltime	Traveltime	Cumulative traveltime	Traveltime	Cumulative traveltime	Traveltime	Cumulative traveltime	Traveltime	Cumulative traveltime	Traveltime	Cumulative traveltime
1	--	--	--	--	--	--	--	--	--	--	--	--
2	5.4	5.4	4.0	4.0	3.3	3.3	2.8	2.8	2.6	2.6	1.9	1.9
3	1.3	6.7	0.9	4.9	0.7	4.0	0.6	3.4	0.5	3.1	0.4	2.3
5	1.3	8.0	1.3	6.2	1.2	5.2	1.2	4.6	1.1	4.2	1.0	3.3

Table 5. Estimated traveltimes of peak dye concentration in Gore Creek, Colorado

[Discharge from Gore Creek at mouth near Minturn 09066510 (site 12); traveltime and cumulative traveltime in hours; shaded areas refer to "Traveltime Estimation Example"; --, no data; ft^3/s, cubic feet per second]

Site no. (table 1 and fig. 1)	Discharge, ft^3/s											
	20		40		60		80		100		200	
	Traveltime	Cumulative traveltime	Traveltime	Cumulative traveltime	Traveltime	Cumulative traveltime	Traveltime	Cumulative traveltime	Traveltime	Cumulative traveltime	Traveltime	Cumulative traveltime
5	--	--	--	--	--	--	--	--	--	--	--	--
6	2.7	2.7	1.8	1.8	1.4	1.4	1.2	1.2	1.0	1.0	0.7	0.7
7	1.6	4.3	1.2	3.0	1.0	2.4	0.8	2.0	0.7	1.7	0.5	1.2
8	2.8	7.1	2.0	5.0	1.6	4.0	1.4	3.4	1.2	2.9	0.8	2.0
9	4.1	11.2	2.7	7.7	2.1	6.1	1.8	5.2	1.6	4.5	1.0	3.0
10	5.5	16.7	3.7	11.4	3.0	9.1	2.5	7.7	2.3	6.8	1.5	4.5
11	3.5	20.2	2.5	13.9	2.0	11.1	1.7	9.4	1.6	8.4	1.1	5.6
12	3.7	23.9	2.5	16.4	2.0	13.1	1.7	11.1	1.5	9.9	1.0	6.6

Site no. (table 1 and fig. 1)	Discharge, ft^3/s											
	300		400		500		600		700		800	
	Traveltime	Cumulative traveltime	Traveltime	Cumulative traveltime	Traveltime	Cumulative traveltime	Traveltime	Cumulative traveltime	Traveltime	Cumulative traveltime	Traveltime	Cumulative traveltime
5	--	--	--	--	--	--	--	--	--	--	--	--
6	0.6	0.6	0.5	0.5	0.4	0.4	0.4	0.4	0.3	0.3	0.3	0.3
7	0.4	1.0	0.4	0.9	0.3	0.7	0.3	0.7	0.3	0.6	0.3	0.6
8	0.7	1.7	0.6	1.5	0.5	1.2	0.5	1.2	0.4	1.0	0.4	1.0
9	0.8	2.5	0.7	2.2	0.6	1.8	0.5	1.7	0.5	1.5	0.5	1.5
10	1.2	3.7	1.0	3.2	0.9	2.7	0.8	2.5	0.8	2.3	0.7	2.2
11	0.9	4.6	0.7	3.9	0.7	3.4	0.6	3.1	0.6	2.9		2.7
12	0.8	5.4	0.7	4.6	0.6	4.0	0.6	3.7	0.5	3.4	0.5	3.2

NWIS-W Data Retrieval page: **http://waterdata.usgs.gov/nwis-w/CO/**.

Discharge at Black Gore Creek near Minturn gage during time of spill = **92** ft^3/s.

B. Estimate traveltime for Black Gore Creek.

Using table 4 and the discharge from step 2A, estimate the arrival time of the spill's peak concentration at the mouth of Black Gore Creek (site 5). If the discharge is not found in table 4, interpolate between values that bracket the reported streamflow or use the higher streamflow value, which will provide a conservative traveltime (Vaill, 2000). Round 92 ft^3/s up to 100 ft^3/s for use in table 4. Traveltime from site 1 to 5 at 100 ft^3/s (from table 4) is 4.2 hours (sum of traveltimes from sites 1 to 2, 2 to 3, and 3 to 5).

The estimated traveltime of the peak in Black Gore Creek: **4.2** hours

Step 3. Determine traveltime for Gore Creek.

Traveltime estimates for Gore Creek (table 5) are based on Gore Creek at mouth near Minturn (site 12).

A. Determine discharge of Gore Creek during the spill.

Real-time streamflow data can be obtained on the internet at the USGS Colorado NWIS-W Data Retrieval page (**http://waterdata.usgs.gov/nwis-w/CO/**)

Discharge at Gore Creek at mouth near Minturn (site 12) during time of spill = 762 ft^3/s.

B. Estimate traveltime for Gore Creek.

Using table 5 and the discharge from step 3A, estimate the arrival time of the spill's peak concentration at the site of interest on Gore Creek (site 8). Round 762 ft^3/s up to 800 ft^3/s for use in table 5. Traveltime from site 5 to site 8 at 800 ft^3/s (from table 5) is 1.0 hour (sum of traveltimes for sites 5 to 6, 6 to 7, and 7 to 8).

The estimated traveltime of the peak in Gore Creek: **1.0** hour

Step 4. Determine total traveltime.

Sum the traveltimes for Black Gore Creek (step 2B) and Gore Creek (step 3B).

Total traveltime = **4.2** + **1.0** = **5.2** hours

Step 5. Estimate arrival time of leading edge.

The traveltime of the leading edge indicates when the contaminant will first reach a specific location. To determine the arrival of the leading edge of the contaminant, multiply the traveltime of the peak concentration (step 4) by 0.89 (Jobson, 1996).

Estimated traveltime of the leading edge:

5.2 hours * 0.89 = **4.63** hours

Longitudinal-Dispersion Coefficients

Longitudinal-dispersion coefficients were calculated for selected stream reaches and are representative of the discharge conditions during traveltime measurements (table 6). Selected stream reaches were chosen on the basis of adequate mixing time. Because the mixing time was not adequate, longitudinal-dispersion coefficients were not calculated for stream reaches between the injection site and the first downstream collection site.

Longitudinal-dispersion coefficients ranged from 17.2 ft^2/s at 4 ft^3/s between sites 2 and 3 to 650 ft^2/s at 144 ft^3/s between sites 7 and 8 (table 6). The longitudinal-dispersion coefficients presented in table 6 provide necessary variables for future stream-contaminant modeling in the Gore Creek watershed.

Table 6. Longitudinal-dispersion coefficients (K_x) for selected stream reaches on Black Gore Creek and Gore Creek, Colorado

[ft^3/s, cubic feet per second; mph, mile per hour; ft^2/s, square feet per second]

Stream reach, by site numbers in table 1 and fig. 1	Index discharge (ft^3/s)	Mean peak velocity of dye cloud (mph)	Longitudinal-dispersion coefficients, K_x (ft^2/s)
2 to 3	4	0.34	17.2
2 to 3	89	2.02	346.5
3 to 5	144	2.03	537.9
5 to 6	11	0.53	24.8
5 to 6	144	2.72	234.7
6 to 7	11	0.77	55.6
6 to 7	144	3.13	293.7
7 to 8	11	0.64	231.8
7 to 8	144	2.58	650.0
8 to 9	11	0.77	172.4
8 to 9	144	3.09	260.6
9 to 10	50	0.88	128.5
9 to 10	590	3.01	380.3
10 to 11	50	1.00	159.6
10 to 11	590	3.33	459.2
11 to 12	50	1.03	63.2
11 to 12	590	3.46	484.5

SUMMARY

In the Rocky Mountains of Colorado, major highways are constructed in stream valleys. In the event of a vehicular accident involving hazardous materials, the close proximity of highways to the streams increases the risk of contaminants entering the streams. Recent population growth has contributed to increased traffic volume along Colorado highways and resulted in increased movement of hazardous materials, particularly along Interstate 70. Gore Creek and its major tributary, Black Gore Creek, are vulnerable to such contamination because Interstate 70 closely parallels the course of these two streams from the headwaters on Vail Pass to the confluence with the Eagle River.

The primary goals of this traveltime study were to determine traveltime and longitudinal-dispersion characteristics and to provide methods of traveltime estimation in Gore Creek and Black Gore Creek for a broad range of discharges. Traveltime measurements are necessary to characterize movement of contaminants that may enter a stream. This traveltime study used a fluorometric dye injection of rhodamine WT and downstream dye detection by fluorometry to measure traveltime characteristics of Gore Creek and Black Gore Creek. At sites downstream from the dye-injection point, grab samples were collected from the approximate center of flow and fluorometry measurements were made using a Turner Designs Model 10 Fluorometer.

Average velocity of the peak dye concentration, during the May traveltime measurements, ranged from 1.20 mph at site 2 on Black Gore Creek to 3.5 mph at site 12 on Gore Creek, whereas during the September traveltime measurements, average velocity of the peak dye concentration ranged from 0.29 mph at site 2 on Black Gore Creek to 1.02 mph at site 12 on Gore Creek. During the May traveltime measurements, discharges ranged from 82 ft^3/s at Black Gore near Minturn to 724 ft^3/s at Gore Creek at Mouth near Minturn, whereas during the September traveltime measurements, discharges ranged from 3.6 ft^3/s at Black Gore near Minturn to 62 ft^3/s at Gore Creek at Mouth near Minturn. Cumulative traveltimes for the peak dye concentration during the May traveltime measurements ranged from 3.45 hours (site 1 to site 3) in the Black Gore Creek to 2.50 hours (site 8 to

site 12) in the Gore Creek, whereas cumulative traveltimes for the peak dye concentration during the September traveltime measurements ranged from 15.33 hours (site 1 to site 3) in Black Gore Creek to 8.65 hours (site 8 to site 12) in Gore Creek. During the September dye injections, beaver dams on Black Gore Creek, between site 1 and the confluence with Gore Creek, substantially delayed movement of the rhodamine WT.

Estimated traveltimes for peak concentration of rhodamine WT dye were calculated for discharges ranging from 20 to 800 ft^3/s for selected stream reaches. Estimated traveltimes were developed by using relationships established from linear-regression methods by relating measured peak traveltime to discharge obtained from two USGS gaging stations [Black Gore near Minturn (09066000) and Gore Creek at mouth near Minturn (09066510)] during those measurements. Resulting estimated peak traveltimes for Black Gore Creek (sites 1 to 5) ranged from 5.4 to 0.4 hour for 20 to 200 ft^3/s and for Gore Creek (sites 5 to 12), 5.5 to 0.3 hour for 20 to 800 ft^3/s.

In the event of a spill into Gore Creek or Black Gore Creek, a stepwise procedure has been developed for water-resource managers to estimate traveltimes of the leading edge and peak concentration of that spill. An example calculating estimated traveltimes for a hypothetical contaminant release in Black Gore Creek is presented in the report.

Longitudinal-dispersion coefficients were calculated for selected stream reaches and are most representative of the discharge conditions during traveltime measurements. Longitudinal-dispersion coefficients ranged from 17.2 ft^2/s at 4 ft^3/s between sites 2 and 3 to 650 ft^2/s at 144 ft^3/s between sites 7 and 8. The coefficients are necessary variables for future stream-contaminant modeling in the Gore Creek watershed.

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USGS/WRIR 02–4037

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